Automated Identification of Stereoelectroencephalography Contacts and Measurement of Factors Influencing Accuracy of Frame Stereotaxy

User manual v0.99

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Content

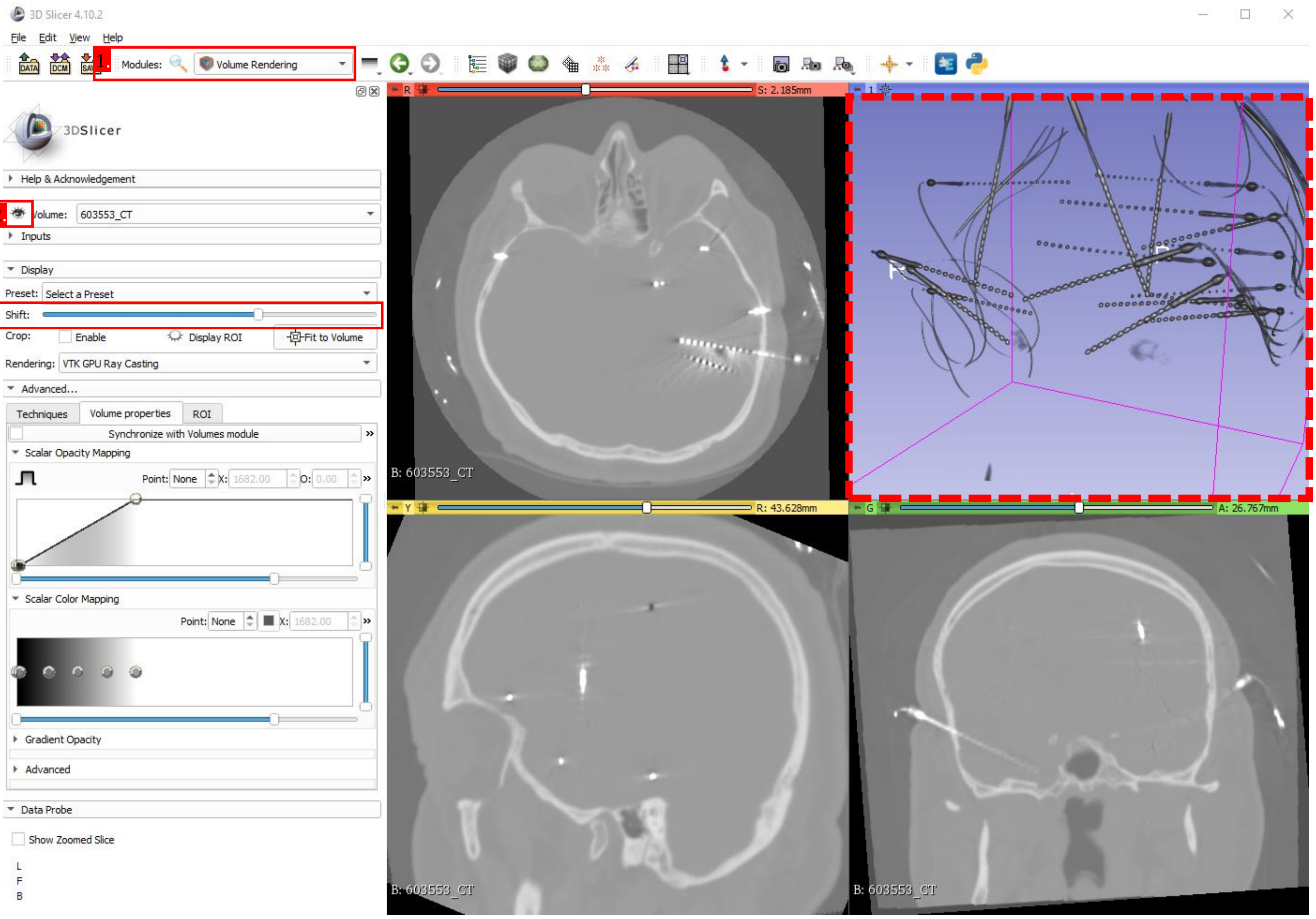
1. Manual electrode initialization

The fully-automated stereoelectroencephalography (SEEG) contact detector requires information of planned electrode trajectories (target and entry points) with electrode naming and length of the electrode (number of contacts). However, this information can be hard to obtain from a neuronavigation system, but the manual electrode labeling can substitute it. This tutorial introduces you to obtain initializing parameters for SEEG contacts detection. The 3D Slicer software (ver. 4.10.2) was selected as an easy tool, but principally any software getting coordinates of the anchor bolts can be used. Newer 3D Slicer version modified *Markups editor*, but obtaining fiducials is principally similar.

Open CT with electrodes (CT-E) in 3D Slicer:

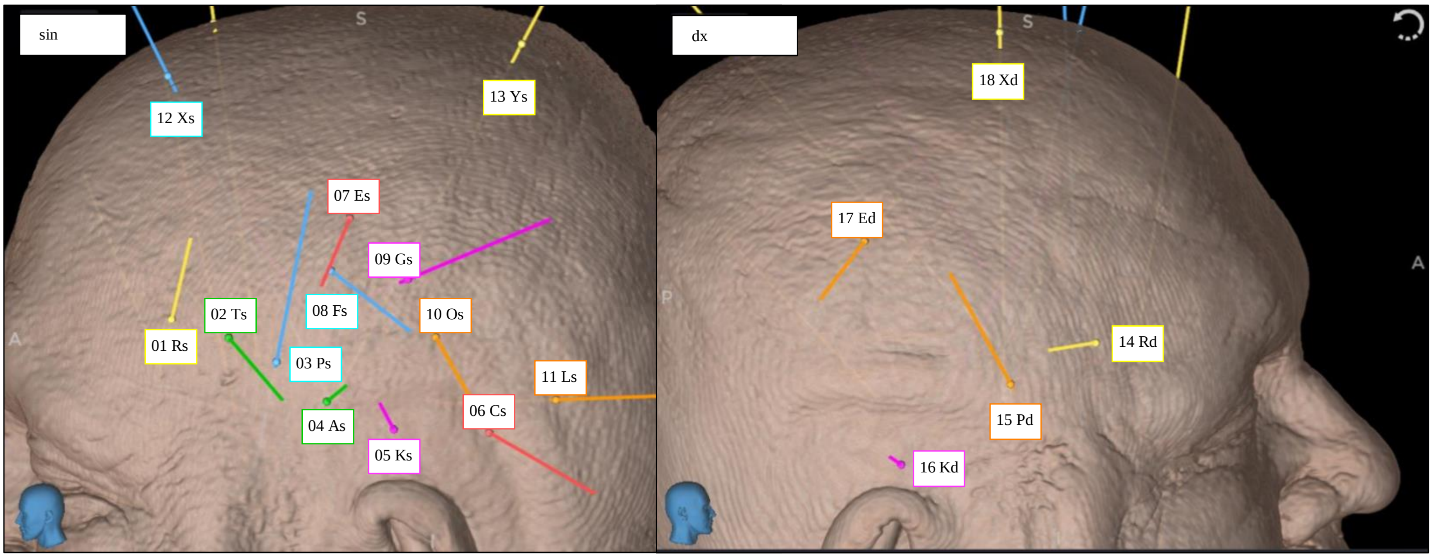
Visualize the CT in 3D (dashed frame, blue window):

1. Use Modules: Volume Rendering
2. Click on the eye for render
3. Shift slider for thresholding of the metal electrodes (Hounsfield unit, *HU*>3000)



1.1. Example: planning scheme.

The first implanted electrode called "Rs" with 18 contacts is visualized by yellow, etc.



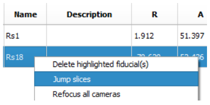
Order	Label	Color	Length (contacts)
01	Rs	yellow	18
02	Ts	green	18
03	Ps	blue	15
04	As	green	15
05	Ks	ping	15
06	Cs	red	15
07	Es	red	18
08	Fs	blue	18
09	Gs	ping	12

Order	Label	Color	Length (contacts)
10	Os	orange	12
11	Ls	orange	15
12	Xs	blue	18
13	Ys	yellow	18
14	Rd	yellow	15
15	Pd	orange	15
16	Kd	ping	15
17	Ed	orange	18
18	Xd	yellow	18

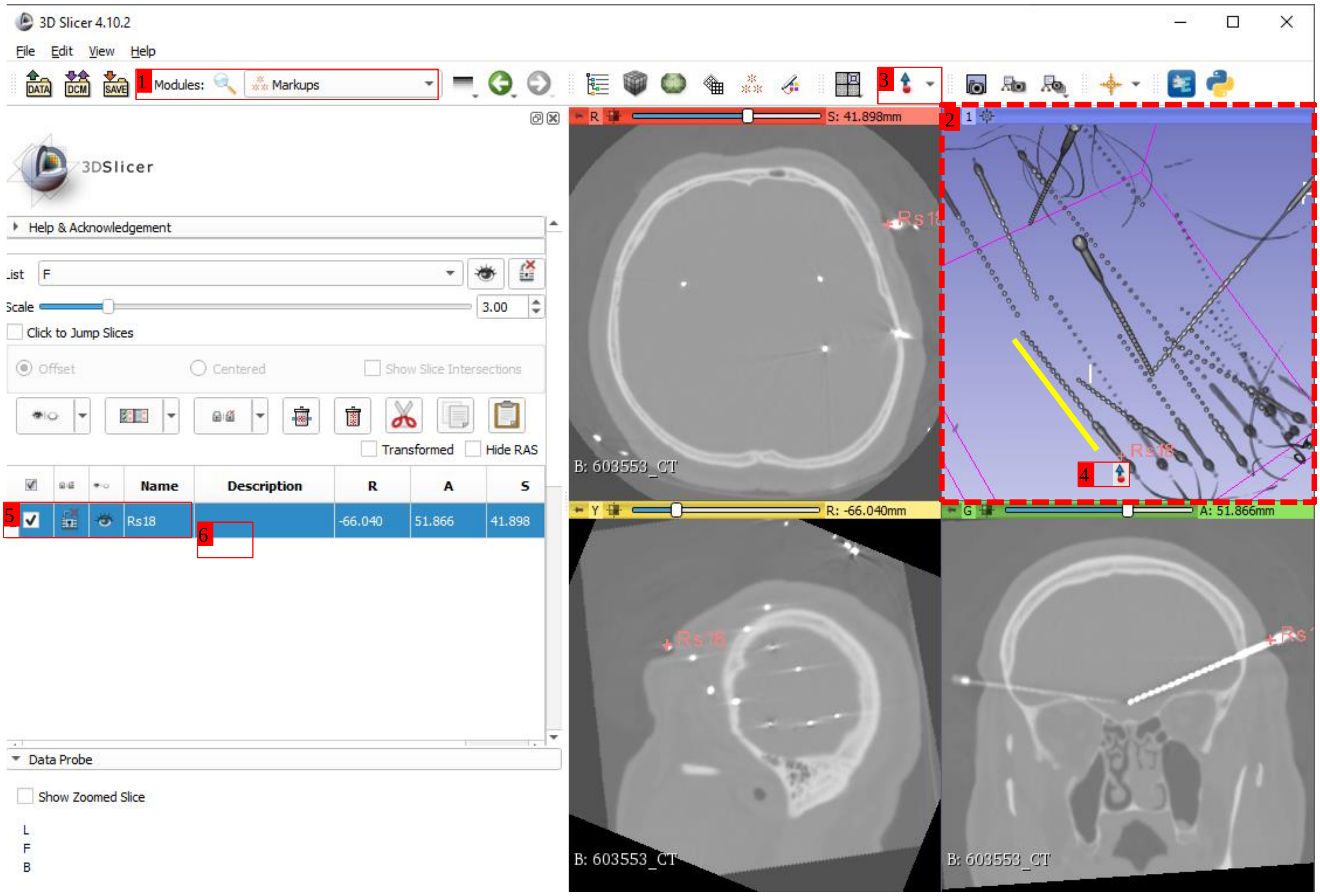
Important: Identify individual SEEG electrodes and name them. Use the **character prefix + numeric suffix**. The prefix defines electrode name, e.g., "Rs". The suffix defines a total number of contacts (Rs18), i.e., 18 channels. The fiducial with name in form (name+length) is placed to the anchor bolt. Subsequently, the detecting algorithm estimates the direction of the anchor bolt and extrapolate the tip by the length of the electrode for GMM initialization.

If the automated detection fail, additionally add the tip-fiducial for more precise GMM initialization with suffix "1", e.g. "Rs1" (electrode tip/ first contact).

1.2. Initializing electrode trajectories:

1. Use Modules: Markups.
2. Rotate CT to view, e.g., electrode Rs. Use the left button for rotation and the right button for zooming.
3. Click on fiducial tool .
4. Click by mouse to place fiducials close, e.g., to anchor bolt, the fiducial "F-1" will be added to the list.
5. Change default fiducial name (F-1) to (e.g., Rs18) in list. Prefix "Rs" is name of electrode, suffix 18 is electrode length (number of contacts).
6. Use right-click for Jump slices 

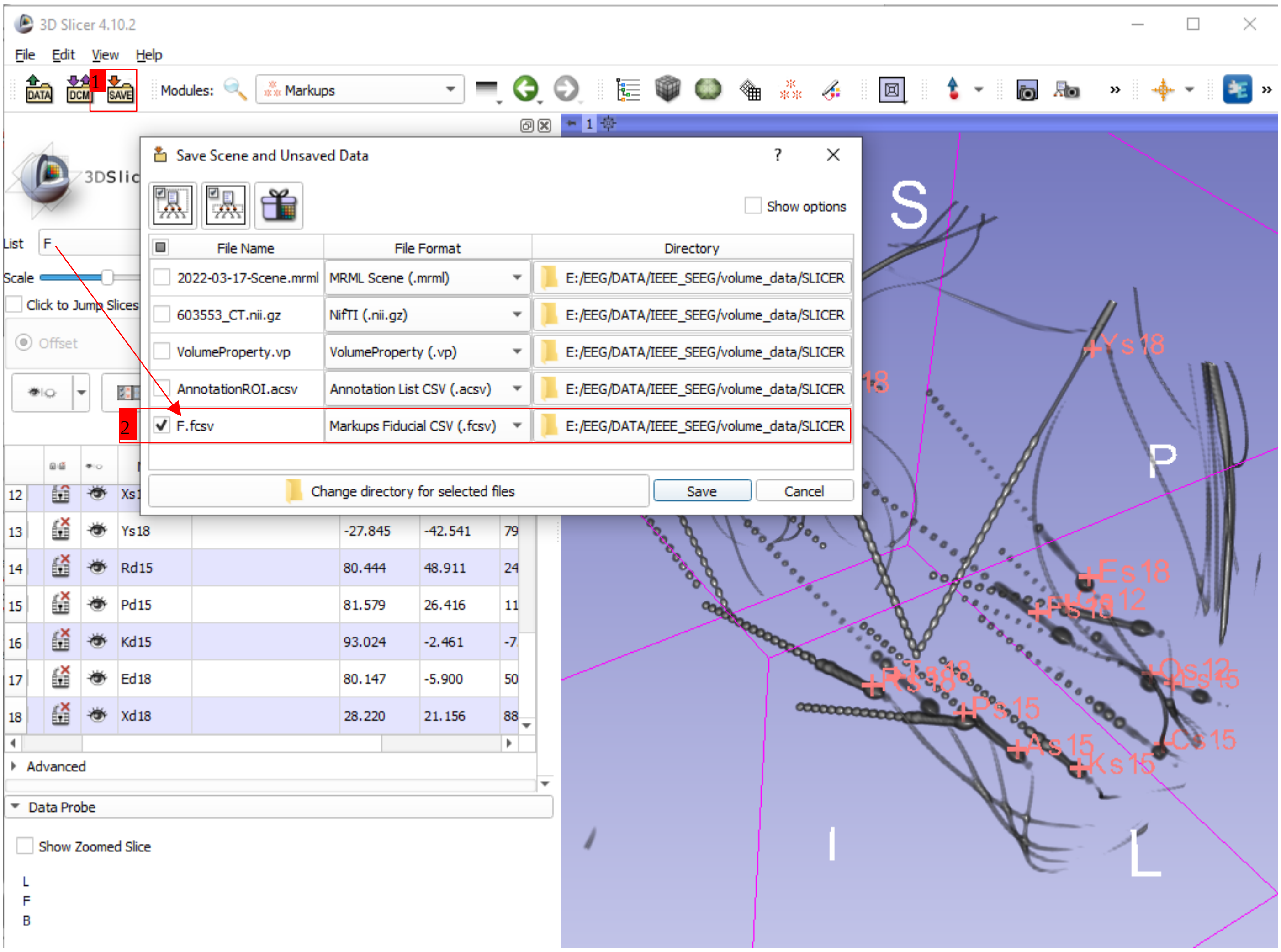
to check the position in 2D (ax, cor, sag). It can be modified by drag & drop, but precision is not required.
7. Optional: If the automatic detection fails, add the fiducial for the electrode tip named with suffix "1", e.g., "Rs1".
8. Reply for all electrodes.



A few minutes later, all electrodes (anchor bolts) are labeled.

Save fiducial list to as *.fcsv:

1) Use the SAVE button and open the menu.
2) Check fiducial list "F" and select file format Markups Fiducial CSV (.fcsv) and set saving directory.



2. MATLAB – MAIN function:

The main script is divided into a few sections that should be run step by step. Neuroimages modalities in NIfTI (*.nii) are linked by full-path to file in structures `MODALITY.path`. The basic requirements are using CT scan with implanted electrodes (CT-E, soft tissue window recommended) and structural MR (T1 recommended). Optional, but strongly recommended is using pre-implantation CT scans (CT-L with frame or other, e.g., low-dose CT of PET) to identify metal implants. CT-L also allows bone thickness, implantation angle, and intracerebral depth measurement. The pipeline below can also be used to measure during the planning trajectory process.

```
CTE.path=fullfile(pwd,'volume_data','603553_CT.nii'); % path to postimplantation with
electrodes (CT-E)
MR.path=fullfile(pwd,'volume_data','603553_T1KL.nii'); % path to MRI for tissue
segmentation (isotropic T1 recommended)

% Optional:
% CTL=[]; % not used
CTL.path=fullfile(pwd,'volume_data','603553_CTNAV.nii'); % path to preimplantaion CT
for automatic masking of metal implants(frame, PET-CT(AC))
```

Initialization section checks the SPM12 installation and adds fields to MODALITY structures (path to parent directory, file name).

```
%% Initialization
% SPM12 toolbox check-------------------------------------------------
spm_dir=what('spm12');
if isempty(spm_dir); error('SPM12 toolbox required'); end
% add toolbox path
addpath(fullfile(pwd,'seeg_epirec'));

% path structures of volumes -----------------------------------------
[CTE, MR, CTL]=init_path(CTE,MR,CTL);
```

Image coregistration uses SPM12 image registration to reorient CTs to MR. The process is improved by the CT originator reset to the center of the image, and MR-CT registration works with thresholded CT (*HU*<2000) to coregister bones, nor metals. All modalities are copied to /SLICER folder and packed by g-zip (*.nii.gz). Warning: The CTs are not resliced. Transformation matrices are modified.

```
%% Image coregistration
% Skip if images are coregistered.
% The coregistration does not use reslicing, only change the orientation
% matrix. The referential image is MR, CTs originator is set to the middle of volume
and coregistered to MR

originator_reset_v2([CTE CTL]); % originator reset

% coregistration: CT is thresholded in HU:10-2000(bone) to remove metal, coregistered
to MR and applied on original CT
vol_corregistration_simple(MR,[CTE CTL]);
```

Tissue segmentation extracts brain tissue models (gray and white matter, cerebrospinal fluid; prefix c1, c2, c3). Segments will be used for masking intracranial space and head ROI.

```
%% Tissue segmentation
% gray matter (c1), white matter (c2), and cerebrospinal fluid (c3)
% Skip if done.
vol_segment(MR)
```

The automated detector requires starting initialization by the planning electrode trajectories, their name, and a number of contacts. Table NAVI can be generated according to information from your planning software. Warning: All electrodes have to be defined. Abbrev.: LAT-lateral (L→R), AP antrior to posterior (A→P), VER-vertical (I→S).

Name	TG: LAT	TG: AP	TG: VER	ENT: LAT	ENT: AP	ENT: VER	S1	S2	S3	N contacts	Order	Color
'Rs'	-12.24	53.87	25.39	-70.62	52.44	44.67	-0.95	-0.02	0.31	18.00	1.00	''
'Ts'	-2.50	41.73	34.35	-63.97	40.15	35.62	-1.00	-0.03	0.02	18.00	2.00	''
'Ps'	-32.43	33.45	2.02	-75.87	28.68	28.31	-0.85	-0.09	0.52	15.00	3.00	''
...												
'Xd'	43.35	18.38	29.07	28.22	21.16	88.62	-0.25	0.05	0.97	18.00	18.00	''

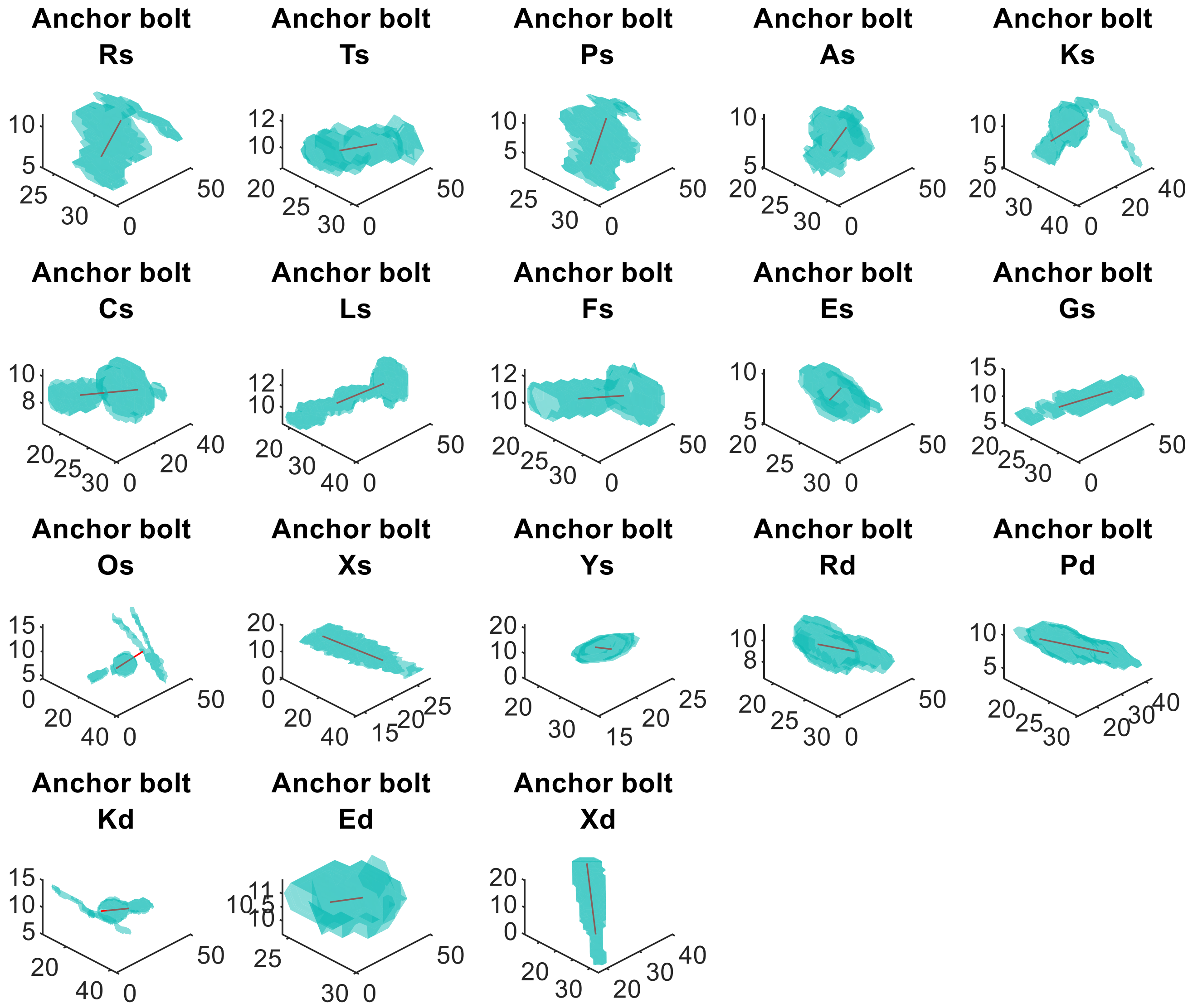
However, use the manual initialization procedure described at the beginning of the document for 3D Slicer. You can place fiducials only to anchor bolts. Marking electrode tips is recommended for complex, close, and crossing electrodes schemes.

```
%% Get electrode list
% The detecting algorithm requires information defined approximate orientation and
length of electrodes.
% The coordinates are in RAS in mm, format composed of:
% LABEL: electrode name
% TG: (LAT|AP|VER)target point (r,a,s)
% ENT: (LAT|AP|VER)entry point (r,a,s)
% S: (S1|S2|S3)directional vector (sr,sa,ss)
% N contacts: number of contacts
% Order: implantation order
% Color: 'HEX' (not used)
%
% This information can be obtained from planning software using target
% (TG) and entry (ENT) points. S=(ENT-TG); S=S/sqrt(sum(S.^2));
% Unavailable TG and ENT coordinates can be set manually, e.g., in 3D Slicer
% and stored in *.fcsv list. The tutorial is attached to toolbox ("Tutorial -
fiducials.pdf")

% Example using FCSV electrode definition

NAVI=get_fcsv_trajectory(fullfile(pwd,'volume_data','SLICER','F.fcsv'),CTE);
```

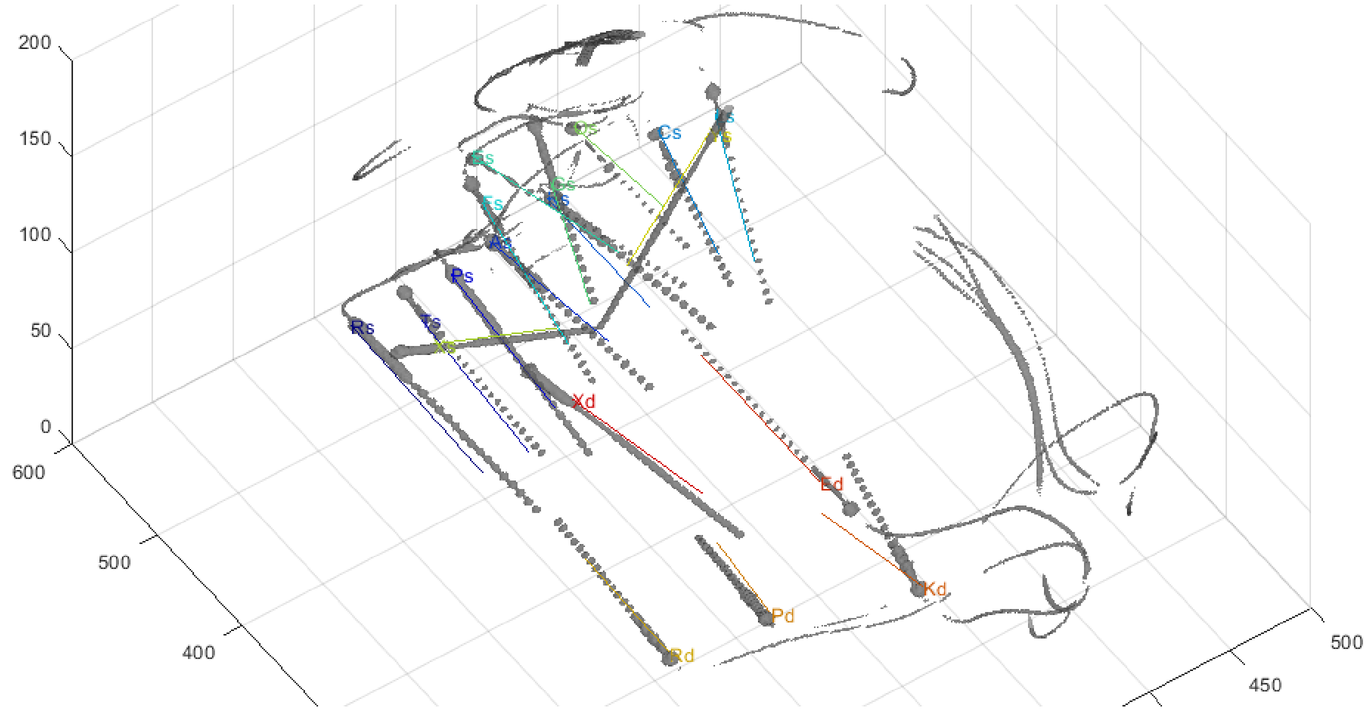
If you use only anchor bolt fiducials, the algorithm estimates their direction and extrapolates them to a head depth for detector initialization. The anchor bolts (transparent isosurface) and their estimated trajectories (red line) will be visualized. You can identify a potentially problematic anchor bolt and add tip fiducial for it.



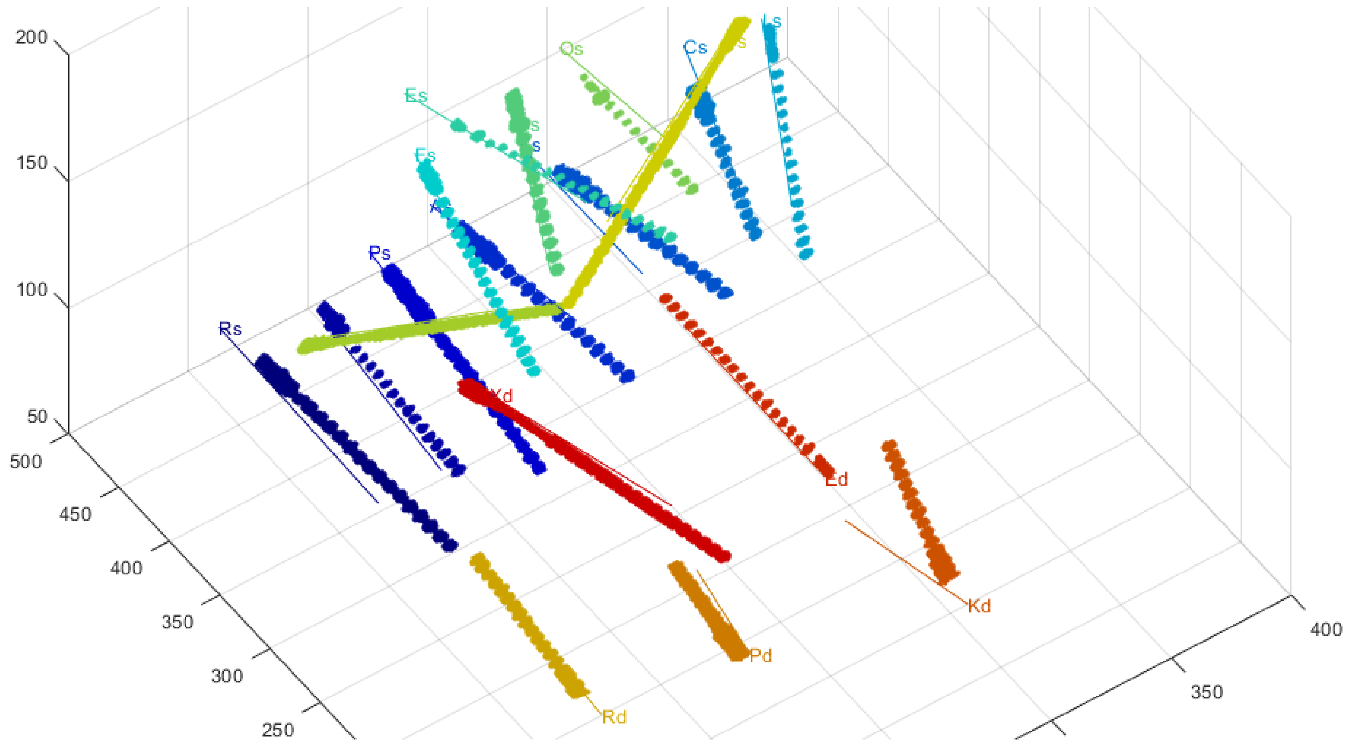
Run automatic detection initialized by `NAVI` table information. The algorithm clusters the electrodes by the GMM algorithm. Each electrode is fitted separately.

```
%% Detect contacts and bone measurement
[ELECTRODES,BONE_MEASURE]=localize_seeg_contacts_v3(NAVI,CTL,CTE,MR);
```

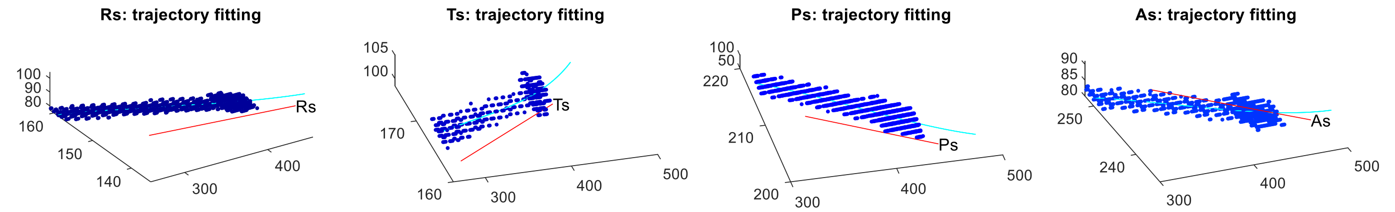
Figure output shows `isosurface` model of metal voxels (gray). The colored and named planning trajectories (or estimated by anchor bolt fiducial) are used for GMM initialization.



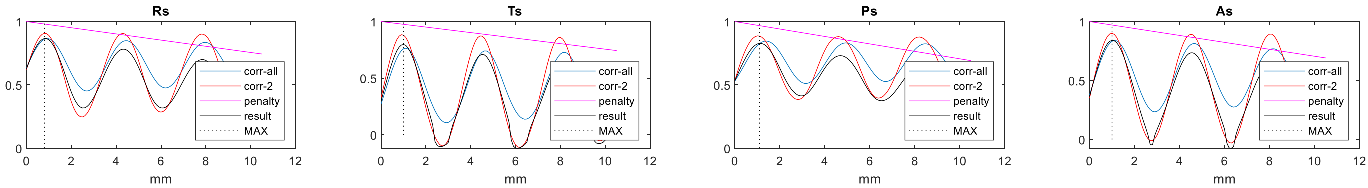
Metal voxels in head ROI_{head} (masked by MR+CT segmentation) are assigned to individual electrodes ROI_{EL}. If you see the wrong assignment, add tip fiducials to problematic electrodes. NOTE: E.g., trajectory "Kd" had been estimated very imprecisely. Hence GMM algorithm identified electrode voxels right.



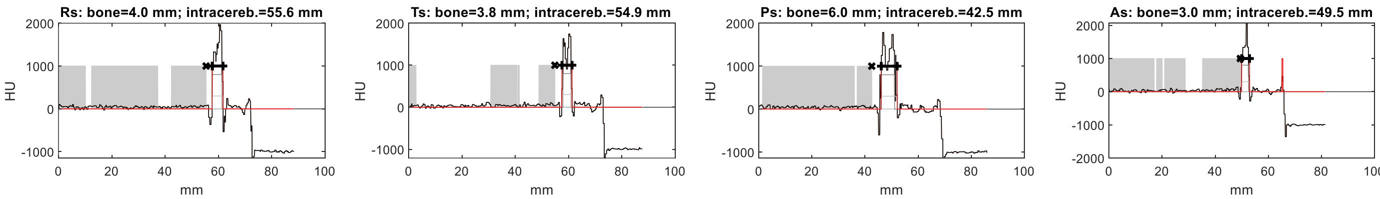
Each electrode ROI$_{EL}$ is fitted for individual contacts identification separately. ROI$_{EL}$ is shown with planned/initialized trajectories (red line) and the final polynomial fit of the central axis (cyan). Example of first four electrodes:



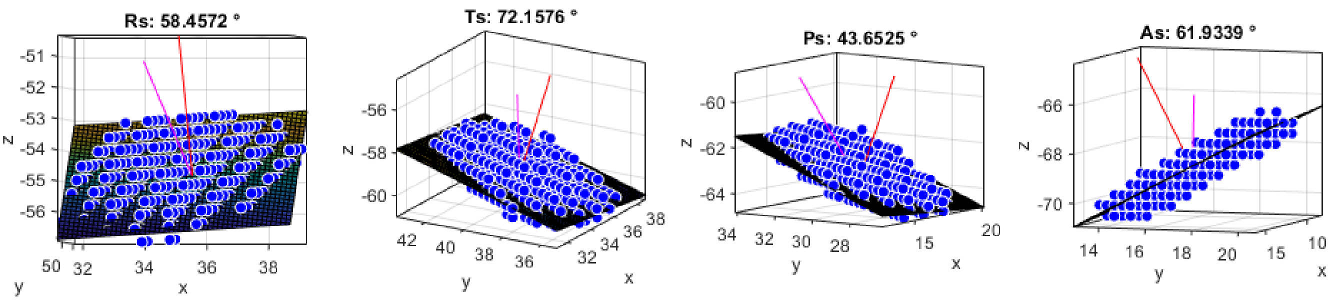
Cross-correlation function between electrodes in CT and moving electrode model shifted through polynomial central axis fit. Maximum defines the best shift of model (dotted black line).



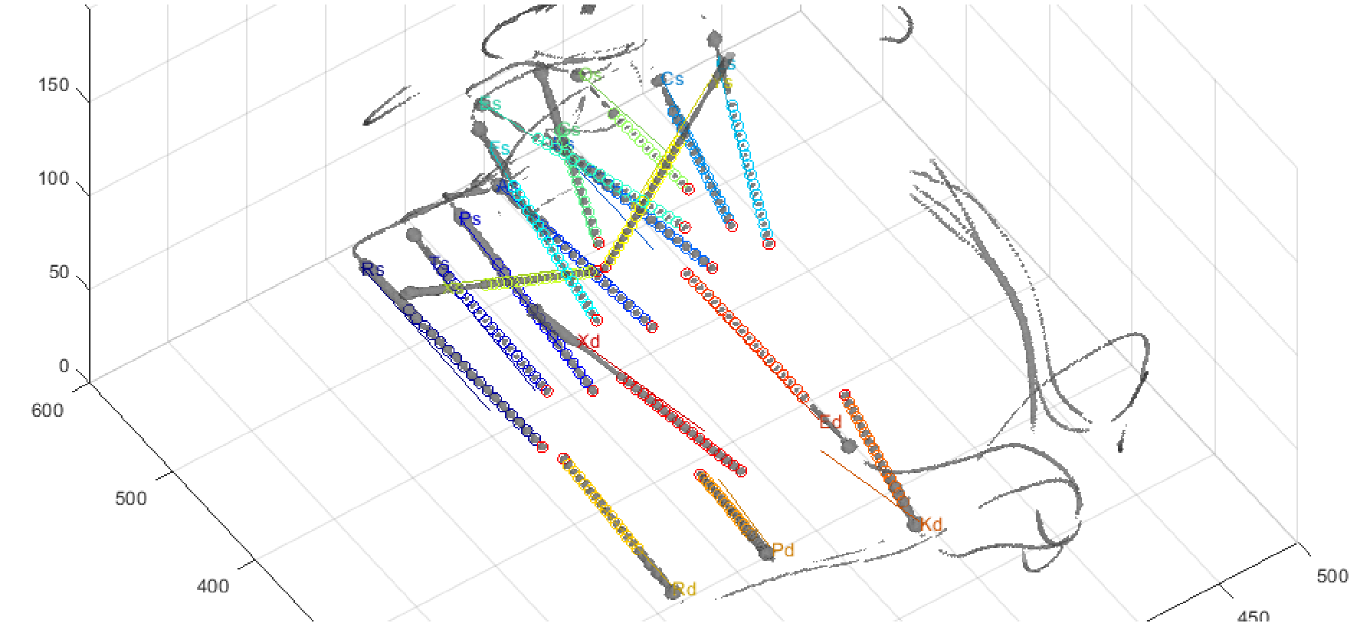
If you use pre-implantation CT without electrodes (CT-L), the bone thickness measurement at the central axis is done. The black line shows *HU* through an electrode; the red line marks bone suspect areas. The extracranial and intracranial entry point is marked by black pluses (+), thickness defines their distance. Gray areas represent grey matter (GM) around electrode trajectory. The entry point to the brain is marked by a black cross (×), the intracerebral depth is measured from the electrode tip.



Implantation angles are estimated at extracranial entry points. Redline represents normal vector of the fitted plane; purple is the electrode trajectory.

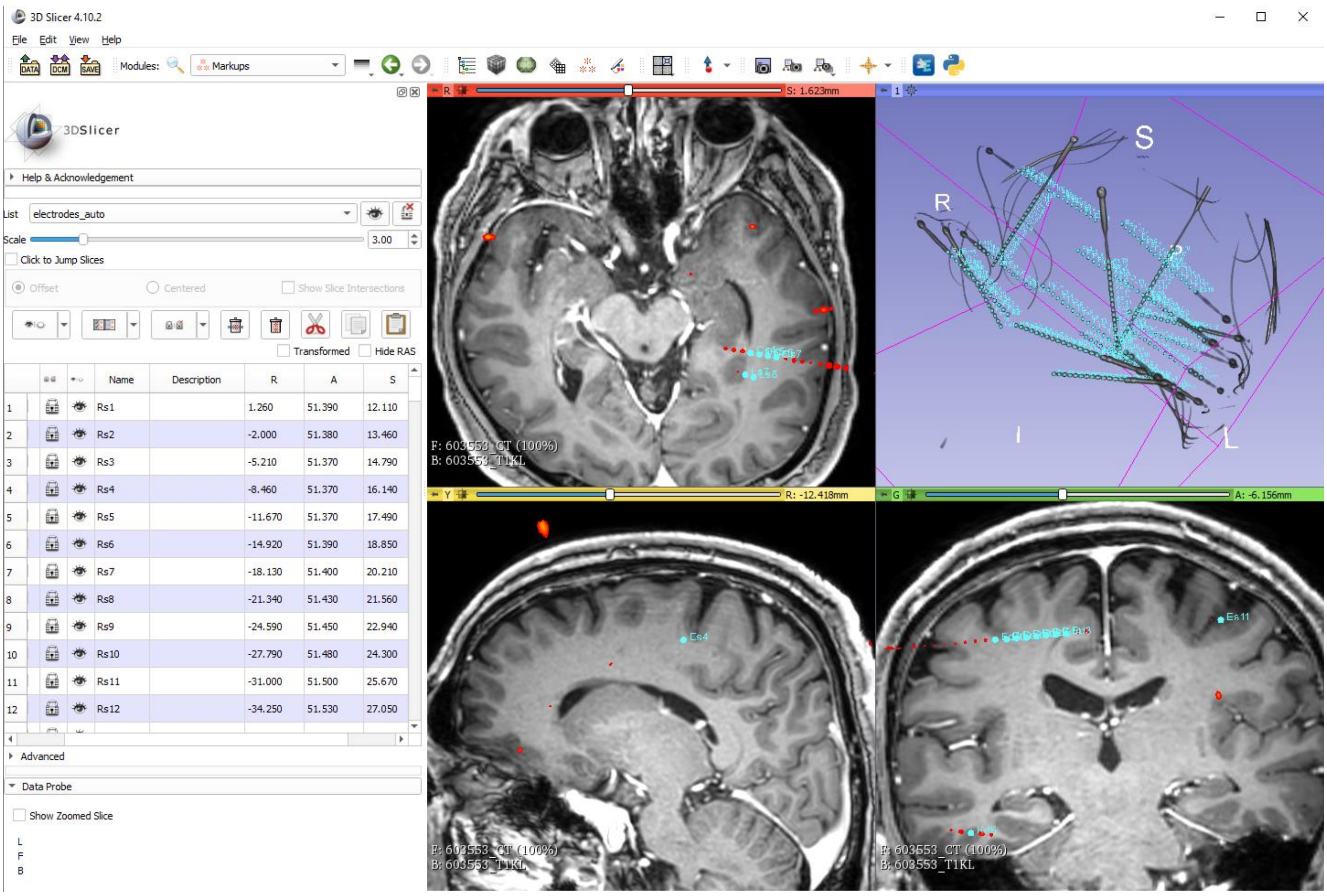


Final contact detections are added to the first figure; the first contacts are marked by a red circle.



Contact coordinates are stored in ELECTRODES variable in form Name, RAS coordinates in mm, as well as the measured bone parameters in BONE_MEASURE.

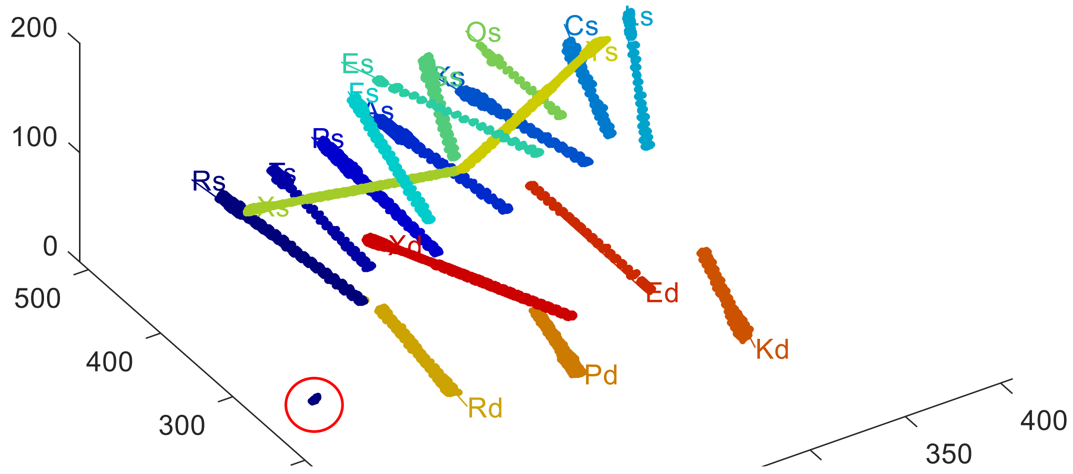
Contacts are also exported to fiducial list "SLICER/electrode_auto.fcsv" for visualization and navigation in 3D Slicer (orange is CT-E *HU*>3000 over MR-T1, blue is detected fiducials). Use DATA icon to load.



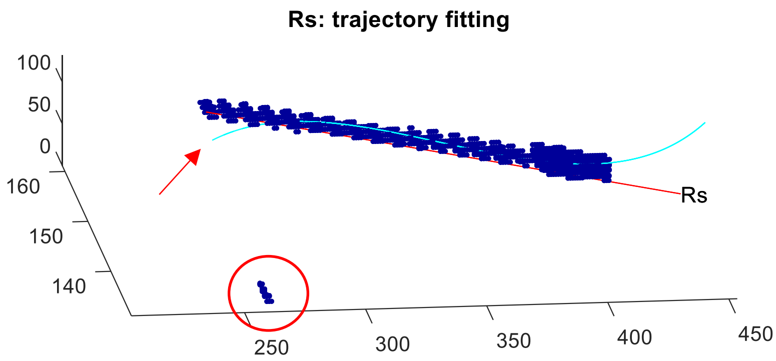
3. What do, when you have not pre-implantation CT (CT-L) and metal implants lead to detection failure.

```
%% Detect contacts and bone measurement
[ELECTRODES,BONE_MEASURE]=localize_seeg_contacts_v3(NAVI,[],CTE,MR);
```

This example of algorithm failure can occur when metal voxels are not SEEG and have not been removed before GMM segmentation using pre-implantation CT, e.g., teeth implant, red circle. Another situation can be caused by wires pushed into the skin, shunts, and other metal objects in the head.



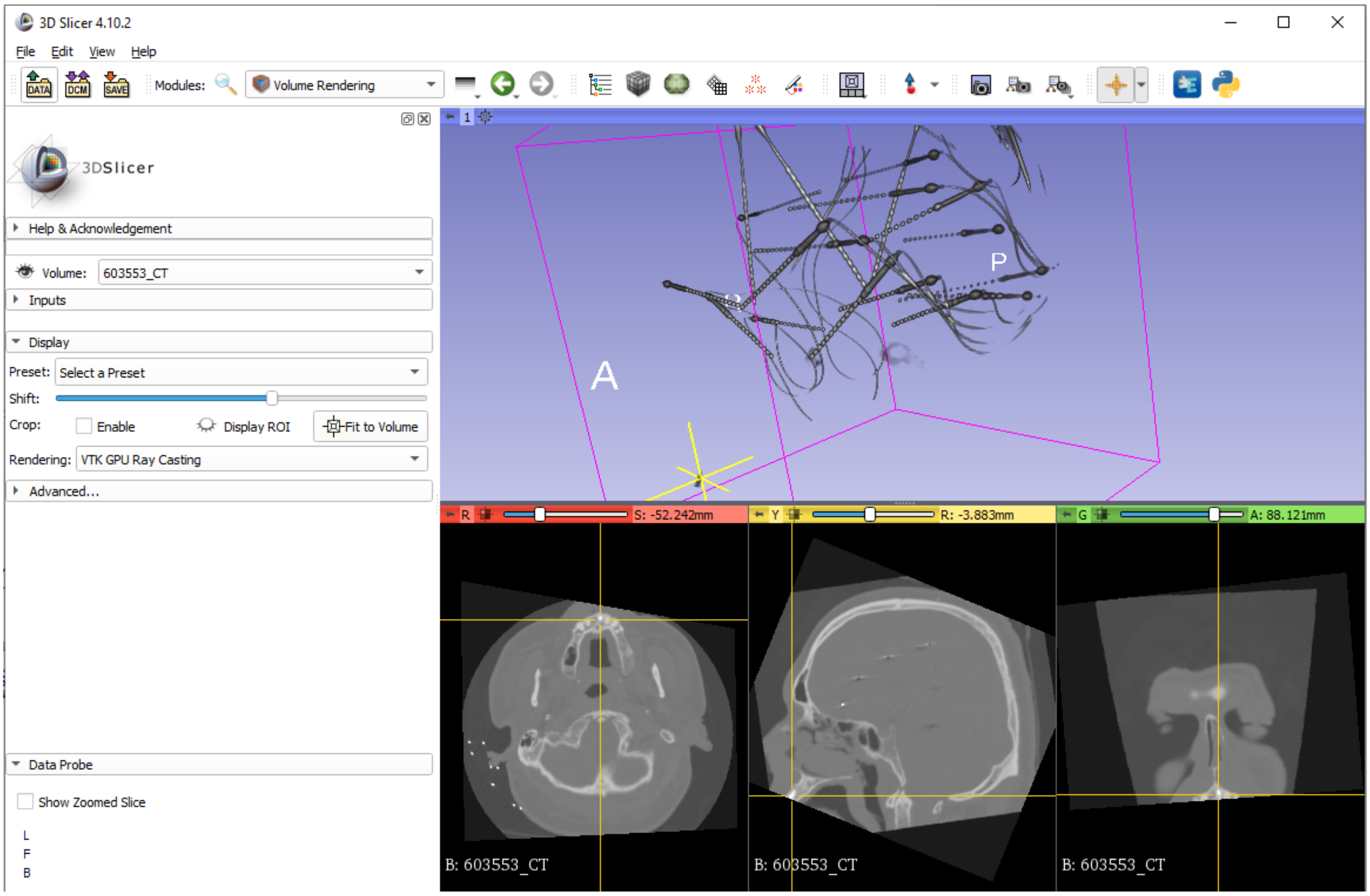
Metal teeth implant is assigned to electrode Rs which distorts an electrode fitting, e.g., at the tip (arrow):



You can create a volumetric mask to exclude non-SEEG voxels, e.g., using 3D Slicer.

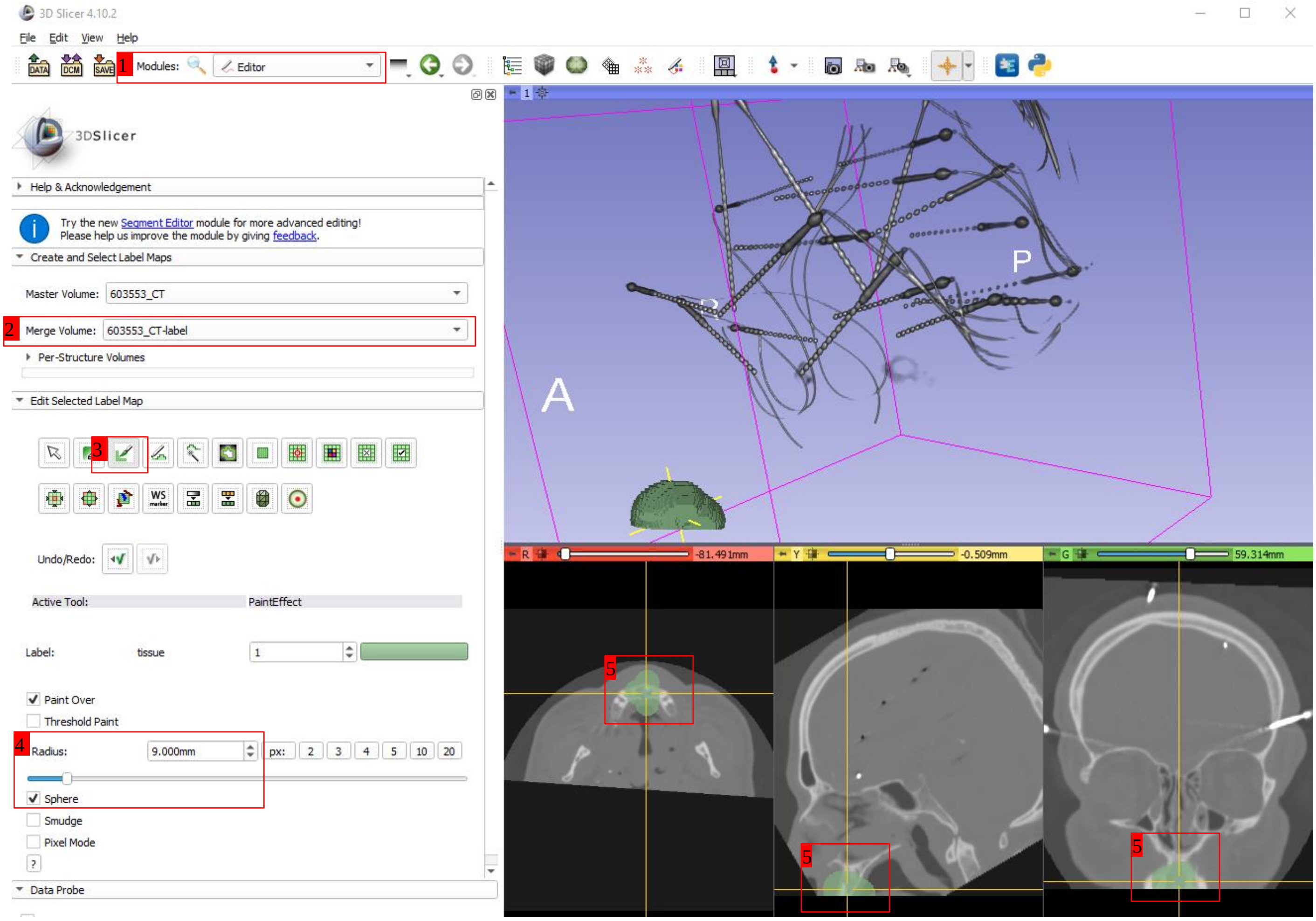
3.1. Manual masking

The inspection in 3D shows a dental implant, which can be masked manually.

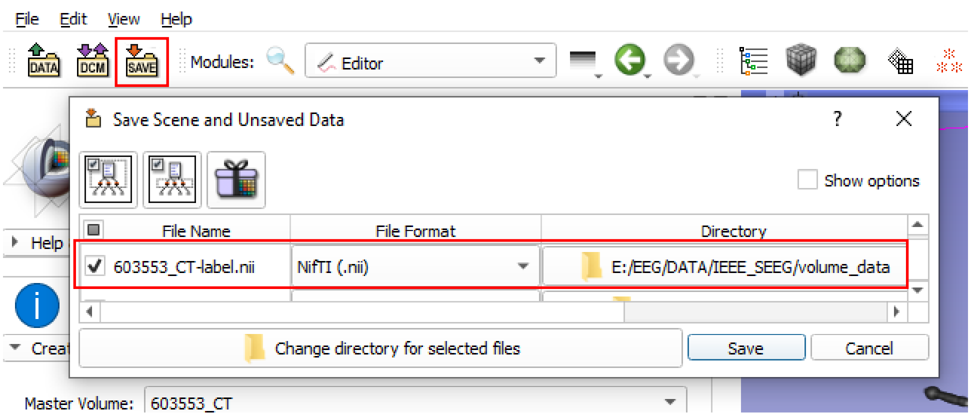


Prepare the mask of metal objects.

1) Use modules: editor (All modules/editor or Legacy/editor)
2) Create corresponding label volume
3) Select painEffect tool
4) Set the appropriate radius and check Sphere (drawing by 3D-ball)
5) Draw region of metals to ignore by the detector. Warning: not mask SEEG electrodes.



Export label as NifTI file (*.nii)



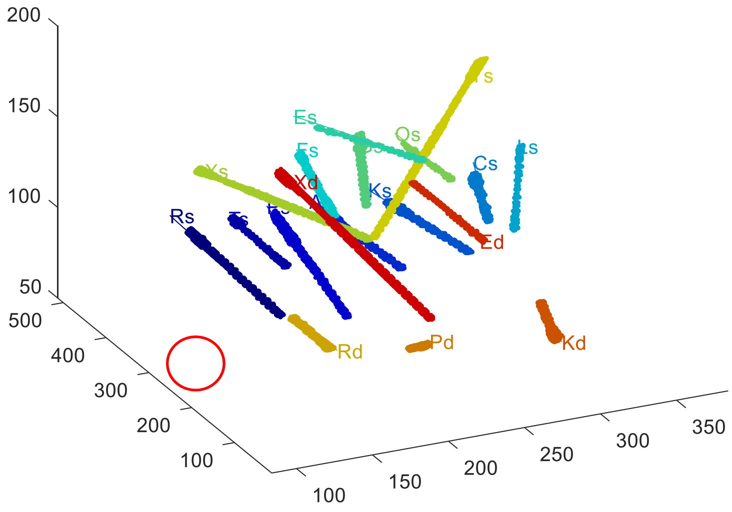
Run detection algorithm with masking file in MATLAB pipeline and run again

```
masking=fullfile(pwd,'volume_data','603553_CT-label.nii');
[ELECTRODES]=localize_seeg_contacts_v3(NAVI,[],CTE,MR,masking);
```

or

```
[ELECTRODES]=localize_seeg_contacts_v3(NAVI,CTL,CTE,MR,masking);
```

Metal teeth implant was excluded from detection (red circle):



4. Measuring in the planning process

When you have precisely planned coordinates (entry and target points), you can measure bone thickness, implantation angle, and intracerebral depth using pre-implantation CT (CT-L). An example of planning trajectories is in "navi_plan_native.csv".

```
NAVI=readtable(fullfile(pwd,'volume_data','navi_plan_native.csv'));
NAVI=NAVI(:,1:7); % Name, Target point, Entry point
```

Name	TG_LAT	TG_AP	TG_VER	ENT_LAT	ENT_AP	ENT_VER
'Xs'	-38.97	12.87	10.04	2.72	57.48	146.97
'Ys'	-38.89	10.68	9.18	-10.31	-94.35	146.97
'Os'	-33.35	-13.83	29.22	-118.02	-12.94	31.22
'Gs'	-34.42	8.57	30.57	-118.02	-20.31	57.20
'Ts'	3.08	41.50	34.36	-118.02	37.39	37.39
'Es'	0.12	-9.75	59.34	-118.02	11.70	64.03
'Fs'	3.00	19.06	49.19	-118.02	6.71	51.28
'Rs'	2.82	52.18	12.18	-118.02	52.00	64.30
...						

```
[~,BONE_MEASURE_palnning]=localize_seeg_contacts_v3(NAVI,CTL,[],MR);
```